



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Carbon Capture and Storage

S.J. Friedmann

October 4, 2007

Oxford Companion to Global Change

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

Carbon Capture and Sequestration Technologies: Status and Future Deployment

Dr. S. Julio Friedmann
Carbon Management Program Leader
Lawrence Livermore National Laboratory
7000 East Ave, Livermore CA 94550, USA
friedmann2@llnl.gov

Introduction

Carbon capture and sequestration (CCS) is the long-term isolation of carbon dioxide from the atmosphere through physical, chemical, biological, or engineered processes. This includes a range of approaches including soil carbon sequestration (e.g., through no-till farming), terrestrial biomass sequestration (e.g., through planting forests), direct ocean injection of CO₂ either onto the deep seafloor or into the intermediate depths, injection into deep geological formations, or even direct conversion of CO₂ to carbonate minerals. Some of these approaches are considered geoengineering (see the appropriate chapter herein). All are considered in the 2005 special report by the Intergovernmental Panel on Climate Change (IPCC 2005).

Of the range of options available, geological carbon sequestration (GCS) appears to be the most actionable and economic option for major greenhouse gas reduction in the next 10-30 years. The basis for this interest includes several factors:

- The potential capacities are large based on initial estimates. Formal estimates for global storage potential vary substantially, but are likely to be between 800 and 3300 Gt of C (3000 and 10,000 Gt of CO₂), with significant capacity located reasonably near large point sources of the CO₂.
- GCS can begin operations with demonstrated technology. Carbon dioxide has been separated from large point sources for nearly 100 years, and has been injected underground for over 30 years (below).
- Testing of GCS at intermediate scale is feasible. In the US, Canada, and many industrial countries, large CO₂ sources like power plants and refineries lie near prospective storage sites. These plants could be retrofit today and injection begun (while bearing in mind scientific uncertainties and unknowns). Indeed, some have, and three projects described here provide a great deal of information on the operational needs and field implementation of CCS.

Part of this interest comes from several key documents written in the last three years that provide information on the status, economics, technology, and impact of CCS. These are cited throughout this text and identified as key references at the end of this manuscript.

When coupled with improvements in energy efficiency, renewable energy supplies, and nuclear power, CCS help dramatically reduce current and future emissions (US CCTP 2005, MIT 2007). If CCS is not available as a carbon management option, it will be much more difficult and much more expensive to stabilize atmospheric CO₂ emissions. Recent estimates put the cost of carbon abatement without CCS to be 30-80% higher than if CCS were to be available (Edmonds et al. 2004).

Carbon capture

CCS has two separate but coupled steps. The first is the separation and concentration of CO₂ from industrial flue streams, chiefly power plants. This first step is commonly called **carbon capture** and usually includes compression and transportation via pipeline. The second involves the injection of CO₂ as a dense, supercritical (liquid-like) phase into deep geological formations. This step is commonly called **geological carbon sequestration**, or GCS. In short, the cost for CCS lies mostly in the capture stage. The risk lies mostly in the sequestration stage. Both steps are needed for a successful project.

In the first step, CCS requires the separation of CO₂ from industrial flue streams and concentration to CO₂ purities of 95% or greater (Thambimuthu et al., 2005). This limits compression costs and makes effective and efficient use of available sequestration resource (subsurface pore volume). Currently, three technology pathways exist for commercial CO₂ capture and separation:

- Post-combustion capture: This involves separation of CO₂ from nitrogen, commonly with chemical sorbents (e.g., monoethanolamine (MEA)).
- Pre-combustion capture: This involves conversion of fuel feedstocks (e.g. coal) into syngas via gasification, steam reformation, or partial oxidation and then shifting the syngas chemically to hydrogen and CO₂, and then separating the H₂ from CO₂. Currently, this last step is commonly done with physical sorbents (e.g., Selexol, Rectisol).
- Oxy-firing combustion: This involves combustion of fuels in a pure oxygen or O₂-CO₂ rich environment such that effectively no nitrogen is present in the flue gas. Separation of O₂ from air (N₂) is required and is the main cost element.

Each of these approaches requires substantial power to run the adsorption and air-separation units, raising operating expenses and increasing the amount of CO₂ emissions produced simply to drive the sequestration process. They also require more capital in plant construction and have differing operational costs and energy penalties. At present, each technology pathway appears equally viable from an economic and thermodynamic standpoint (Thambimuthu et al., 2005; Rao et al. 2006; MIT 2007).

Industry has substantial experience with each of these technology pathways, chiefly from operation of hydrogen plants, fertilizer plants, refineries, and natural gas processing facilities. CO₂ has been separated from industrial flue streams at scales much greater than 1 MMt CO₂/y (270,000 t C/y). Similarly, CO₂ has been separated from small-scale power plants, and the technology to scale these operations to plants of 200 MW or greater exists. Large pipelines transport millions of tons of CO₂ hundreds of kilometers, and millions of

tons of CO₂ and other acid gases are compressed and injected into geological formations every year. Thus, a great deal is known about carbon capture, separation, and transportation, and many OECD countries have regulatory frameworks in place to accommodate the permitting of separation facilities and pipelines.

Cost remains an important barrier to wider commercial deployment. However, as the concepts for geological carbon sequestration are proven to be reliable for current power plant technology, improved power plant designs are expected to be able to bring down sequestration costs dramatically. This year, several large pilot projects are testing pre-, post-, and oxy-fired combustion tests at the 4-5 MW scale, a necessary precursor to broad commercial deployment. A number of technologies claim to be able to capture and separate CO₂ at \$9-11/ton CO₂, less than half the best available technology. As the results from these and future tests are made public, decision makers and investors will be able to plan better for plant economics and design.

Geological sequestration

A number of geological reservoirs appear to have the potential to store many 100's – 1000's of Gt of CO₂ (Benson and Cook, 2005). The most promising reservoirs are porous and permeable rock bodies at depth (Figure 1).

- *Saline formations* contain brine in their pore volumes, commonly with salinities greater than 10,000 ppm.
- *Depleted oil and gas fields* have some combination of water and hydrocarbons in their pore volumes. In some cases, economic gains can be achieved through enhanced oil recovery or enhanced gas recovery (Stevens, 1999; Oldenburg et al., 2004; Jarrell et al., 2002). Substantial CO₂-enhanced oil recovery already occurs in the US with both natural and anthropogenic CO₂. These fields provide much of the knowledge base we have about the potential issues related to CO₂ sequestration.
- *Deep coal seams*, often called unmineable coal seams, are composed of organic minerals with brines and gases in their pore and fracture volumes that can preferentially adsorb and bind CO₂ as well as store it in pores and minor fractures.

Because of their large storage potential and broad distribution, it is likely that most geological sequestration will occur in saline formations. However, initial projects have been proposed for depleted oil and gas fields, accompanying enhanced oil recovery, due to the high density and quality of subsurface data and the potential for economic return. Although there remains some economic potential for enhanced coal bed methane recovery much less is known about this style of sequestration (Benson & Cook, 2005; MIT, 2007, NPC 2007, US DOE 2007a). Even less is known about sequestration in basalts. As such, many workers are not convinced of the economic viability of sequestration projects in coal, basalts, or oil shales given today's technology and understanding (US DOE 2007b).

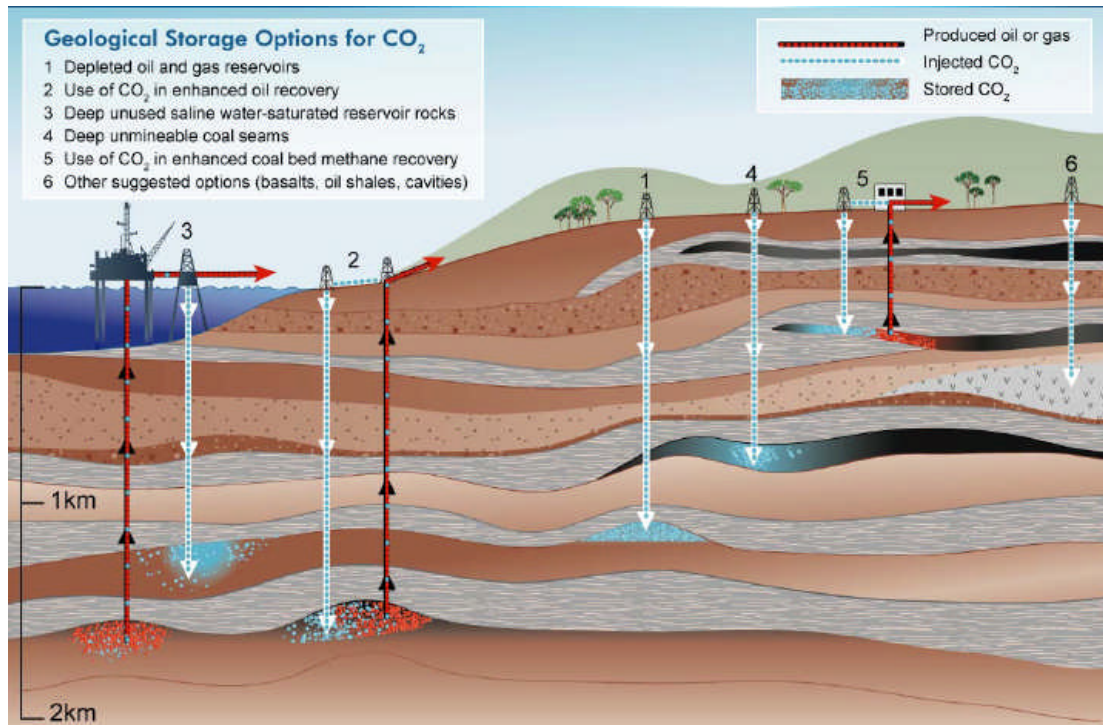


Figure 1: Options for storing CO₂ in underground geological formations. After Benson and Cook (2005).

Storage of large CO₂ volumes in geological formations requires that the CO₂ be relatively dense, so that storage capacity is efficiently used. Given typical geothermal gradients and hydrostatic loads, CO₂ is likely to be in a **supercritical** state at most target sites greater than 800 m depth (e.g., Bachu, 2000). At the likely range of injection pressures and temperatures for most projects, CO₂ would be buoyant and gravitational forces would push CO₂ upward from the injection point.

Consequently, trapping mechanisms are needed to store CO₂ effectively. For depleted oil and gas fields or for saline formations, CO₂ storage mechanisms are reasonably well defined and understood (Figure 2). CO₂ sequestration targets will require *physical barriers* to CO₂ migration out of the crust to the surface. These barriers will commonly take the form of impermeable layers (e.g., shales, evaporites) overlying the sequestration target. This storage mechanism is highly or directly analogous to that of hydrocarbon trapping, natural gas storage, and natural CO₂ accumulations. At the pore scale, *capillary forces* can immobilize a substantial fraction of a dispersed CO₂ bubble, commonly measured to be between 5 and 25% of the CO₂-bearing pore volume. The volume of CO₂ trapped as a residual phase is highly sensitive to pore geometry, and consequently is difficult to predict; however, standard techniques can measure residual phase trapping directly in the laboratory with rock samples.

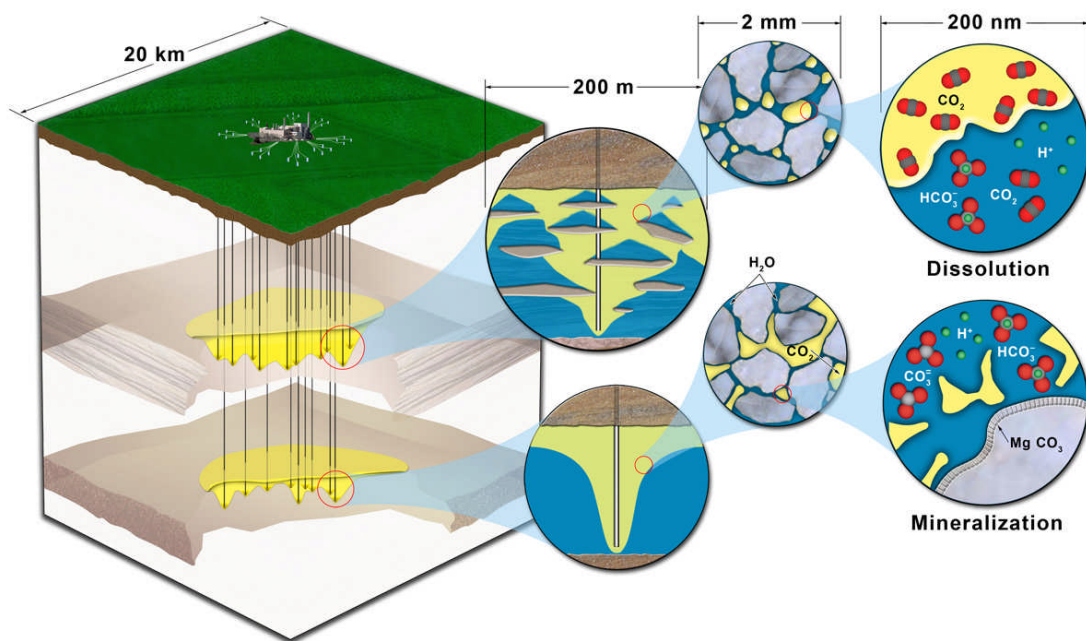


Figure 2: Schematic diagram of large injection at 10 years time illustrating the main storage mechanisms. All CO₂ plumes (yellow) are trapped beneath impermeable shales (not shown). The upper unit is heterogeneous with a low net percent usable porosity, whereas the lower unit is homogeneous. Central insets show CO₂ as a mobile phase (lower) and as a trapped residual phase (upper). Right insets show CO₂ dissolution (upper) and CO₂ mineralization (lower). After MIT (2007).

Once in the pore volume, the CO₂ will *dissolve* into other pore fluids, including hydrocarbon species (oil and gas) or brines. Depending on the fluid composition and reservoir condition, this may occur rapidly (seconds to minutes) or over a period of tens to hundreds of years. Once dissolved, the CO₂-bearing brines are denser than the original brines, and so the strong buoyant forces of free-phase gas are replaced by small downward forces. Over longer time scales (hundreds to thousands of years) the dissolved CO₂ may react with minerals in the rock volume to *dissolve or precipitate* new carbonate minerals. For the majority of the rock volume and major minerals, this process is slow, and may take hundreds to thousands of years to achieve substantial storage volumes. Precipitation of carbonate minerals permanently binds CO₂ in the subsurface; dissolution of minerals generally traps CO₂ as an ionic species (usually bicarbonate) in the pore fluid.

Although substantial work remains to characterize and quantify these mechanisms, the current level of understanding can be used today to develop estimates of the percentage of CO₂ that can be stored over some period of time. Confidence in these estimates is bolstered by studies of hydrocarbon systems, natural gas storage operations, hazardous waste injection, and CO₂-enhanced oil recovery (CO₂-EOR). In the case of EOR, CO₂ has been injected underground for over 30 years. Current evaluations of CCS effectiveness based on our current understanding of trapping mechanisms estimate that more than 99.9% of injected CO₂ can be reliably stored over 100 years, and it is likely that 99% of CO₂ can be reliably stored for 1000 years (Benson and Cook 2005). While

these estimates are predicated on the assumption of careful siting and due diligence before injection, it reflects the view that the crust contains sites that are generally well configured to store CO₂ effectively.

Large-scale commercial deployment

In order to achieve substantial GHG reductions, geological storage needs to be deployed at a large scale (Friedmann, 2006), there must be minimal leakage from the underground storage reservoirs back to the atmosphere, and there must be minimal impact on other uses of the subsurface environment and the resources it contains. The issue of scale dominates deployment of GCS (Pacala & Socolow 2004; Edmonds et al. 2004; McFarland 2004; US CCTP 2005). These volumes would have geological carbon sequestration, providing 25-75 Gt C over 50 years, or 15-43% of emissions reduction needed to stabilize atmospheric CO₂ levels at 550 ppm (Pacala and Socolow 2004).

Today there are three well-established large-scale injection projects with an ambitious scientific program that includes monitoring and verification (Table 1): Sleipner in Norway (Arts et al., 2004), Weyburn in Canada (Wilson and Monea 2004), and In Salah in Algeria (Riddiford et al. 2004). Each project has injected CO₂ at the rate of ~1 MM tons/y (~280,000 t C/y). Each project has had a substantial supporting science program or anticipates one. Substantial information can be found on each project in the literature, and summaries can be found in Benson and Cook (2005).

Table 1: Current and pending large CO₂ injection projects

Site	Location	Reservoir class	Reservoir type	Permeability	Seal type	Start date*
Sleipner	Norway	Offshore Saline Fm.	Deep-water Sandstone	V. high	Thick shale	1996
Weyburn	Canada	Onshore EOR	Ramp carbonate	Moderate	Evaporate	2000
In Salah	Algeria	Onshore Sandstone	Fluvial/tidal sandstone	Low	Thick shale	2004
FutureGen	US	Onshore Saline Fm.	Fluvial sandstone or shelf carbonate	Moderate	Thick shales or evaporites	2012
ZeroGen	Australia	Onshore EOR/Saline	Fluvial/deltaic sandstone	Low-moderate	Shale	2011
Snohvit	Norway	Offshore Saline Fm.	Fluvial sandstone	Moderate	Shale/evap.	2008
DF1/Miller	UK	Offshore EOR	Deep-water sandstone	Moderate - high	Thick shale	2011
DF2/Carson	US	Onshore EOR	Deep-water sandstone	Moderate - high	Thick shale	2012
Latrobe Valley/Monash	Australia	Offshore EOR/Saline	Fluvial/deltaic sandstone	High	Thin and thick shales	2011
Gorgon	Australia	Offshore Saline Fm	Deep-water sandstone	Moderate	Thick shales	2009

Hauten/ Draugen	Norway	Onshore/ Offshore Saline Fm.	Deep-water sandstone	High – V. high	Thick shales	2010
Phase III Regional Partnerships	US	Varying, but mostly Saline Fm.	Varying	Varying	Varying	2010

** = date of first injection or planned first injection of CO₂*

These projects have sampled a wide array of geology (Table 3) with varying trapping mechanisms, injection depths, reservoir types, and injectivity. Each of these projects appears to have ample injectivity and capacity for success, and none has detected CO₂ leakage of any significance. In addition to the three sequestration projects, many industrial applications have injected large volumes of CO₂ into the subsurface. EOR operations in W. Texas, New Mexico, Colorado, Wyoming, Oklahoma, Mississippi, Trinidad, Canada, and Turkey have individual injection programs as large as 3 MM t CO₂/y (~820,000 t C/y) and cumulative anthropogenic emission injections of ~10 MM t CO₂/y (2.7 MM t C/t) (Kuuskraa et al., 2006). It should be said that the monitoring and verification program at each site varies substantially (MIT 2007). In many EOR projects, there is almost no monitoring beyond that required for CO₂ flood operations (Jarrell et al 2002).

A significant number of large-scale injection projects are expected to begin within the next five years, which will provide dynamic new opportunities to design and implement and test new monitoring strategies (Table 3). These projects will sample a substantial range of geology and on a global basis will be able to provide the opportunity to learn about the scientific, technical, and operational concerns. This list will be out of date when it is published – new projects are being announced at an astonishing rate.

Science and technology status

As discussed above, the knowledge of trapping mechanisms and the successes of the three large projects provide substantial information. These are augmented by studies of naturally occurring CO₂ systems, (IEA GHG 2005), natural gas storage facilities, hazardous waste disposal, acid gas injection, and CO₂ -EOR (Benson & Cook 2005). This knowledge provides a firm foundation for commercial action and a nascent foundation for the development of regulation, standards, and legal frameworks for sequestration (Wilson et al., 2003). GCS itself, however, drives study into specific technical and scientific challenges associated with the central elements of site characterization, selection, operation, and monitoring (US DOE 2007a; Wilson et al. 2007). Forward investigation around these topics will enhance the technical and operation understanding of commercial GCS.

Monitoring and Verification (M&V)

Monitoring and verification must detect and track CO₂ in the deep subsurface near injection targets, in the shallow subsurface, and above ground. Monitoring and verification studies are a chief focus of many applied research efforts. The US Department of Energy has defined M&V technology development, testing, and deployment as a key element to their technology roadmap (US DOE, 2007a), and one

new European Union program (CO2ReMoVe) has allocated €20 million for monitoring and verification. Some form of M&V will be required at commercial sites, but the extent of monitoring required by regulators, operators, or financiers remains uncertain. Many geophysical and geochemical methods are sufficiently well understood for them to be used to make reasonable performance predictions at candidate storage sites (Benson et al. 2004; Burton et al. 2007). Testing which of these approaches will be the most valuable for a given geological environment remains to be determined.

Key science and technology gaps

Despite the tremendous amount of applied and basic knowledge, there remain both cross-cutting and-site specific topics for investigation (Friedmann 2007b). From an applied perspective, the National Energy Technology Laboratory has written and annual plan to identify and address key technology gaps (US DOE 2007a). Conversely, a recent report by the US DOE Office of Science (US DOE 2007b) is meant to be focus on a set of basic science gaps and questions. While these documents are not meant to be comprehensive, they accurately reflect the current state of knowledge and potential to continue scientific investigations in GCS.

Deployment Challenges

Despite the current gaps in sequestration science and technology, commercial projects have begun and are ready to proceed with confidence in their success. Today, we know enough to safely and effectively execute key tasks around single large-scale injection projects:

- Characterize a site
- Design and operate the project
- Monitor the CO₂ injection
- Mitigate problems that might arise
- Close and abandon the project

Although this knowledge is currently being brought to bear on specific injection projects around the world, greater scientific understanding is required to develop tools, regulations, and standards for deployment of multiple million ton injections in thousands of wells nationwide and worldwide across a range of geological settings. This affects both sides of the deployment rubric over the project life cycle (Friedmann 2007a; Wilson et al. 2007). Potential operators must execute a set of tasks to prepare for and execute injection permitting and operation. Similarly, potential regulators, investors, insurers, and public stakeholders require information to make decisions. Part of the challenge is to provide a technical basis for each set of actors to make decisions concerning the minimal amount of information needed to serve all stakeholders (Friedmann 2007a; Burton 2007).

While many possible goals and terms may be pursued in site characterization, it is difficult to imagine the success of a large-scale injection project without knowledge of three parameters. These are *injectivity*, *capacity*, and *effectiveness* (Friedmann 2006). In general terms, injectivity and capacity may be estimated by conventional means, such as special core analysis, regional and local structural and stratigraphic mapping, and simple multi-phase fluid flow simulations. However, there are n explicit standard measures of effectiveness. Ultimately, characterizations must rely on estimates of geomechanical

integrity, hydrodynamic stability, and seal continuity for the rock system, fault system, and well system (Streit and Hillis 2004; Hovorka et al. 2006; Chiaramonte et al. 2006; Burton et al. 2007).

Given this complexity, it is not broadly accepted today what terms constitute effective storage. The FutureGen project's request for proposals (FutureGen Alliance 2006) laid out a set of minimum criteria for acceptance. These criteria are based on expert opinion, laboratory experimentation, analog studies, and simulations. However, there is no empirical data set from multiple geological carbon sequestration deployments that provide a standard for characterization of site effectiveness.

Hazards Assessment and Risk Management

Supercritical CO₂ is buoyant and will seek the earth's surface; therefore, CO₂ injection carries the possibility of leakage. Importantly, CO₂ leakage risk will not be uniform across all sites, thus CO₂ storage sites will have to demonstrate minimal risk potential in their site characterization plans (Bradshaw et al. 2004). Based on analogous experience in CO₂ injection such as acid gas disposal and enhanced oil recovery, these risks appear to be less than those of current oil and gas operations (Benson and Cook 2005).

The direct hazards associated with geologic sequestration fall into three distinct categories:

- hazards associated with the release of the carbon dioxide to the earth surface
- hazards associated with release into groundwater and subsequent degradation
- hazards associated with earth movement caused by the injection process itself.

The hazards themselves in turn are associated with failure mechanisms and triggers (Table 2). Potential triggering of events associated with these hazards could lead to undesired consequences. As such, it is an important goal to identify and understand these hazards in order to avoid triggering hazard events. Identification and characterization of these hazards is the critical first step to managing the risks at a site. They also serve as the basis for a quantitative probabilistic risk assessment (PRA). A robust PRA cannot be made today due to substantial scientific and technical gaps. However, the hazards associated with a site can be identified, mapped, characterized, and parameterized sufficiently to avoid failure or (alternatively) avoid selecting a bad site.

Table 2: CCS-Related Earth & Atmospheric Hazards (after Friedmann 2007a)

Atmospheric release hazards	Groundwater degradation hazard	Crustal deformation hazards
Well leakage	Well leakage	Well failure
Fault leakage	Fault leakage	Fault slip/leakage
Caprock leakage	Caprock leakage	Caprock failure
Pipeline/operational leakage		
	Water displacement and far-field saline intrusion	Induced seismicity

		Subsidence/tilt
--	--	-----------------

Development of Standards and Protocols

Understanding risk requires understanding the controlling parameters in the geological environment elected for the sequestration sites. The risk elements described so far for earth and atmospheric hazards suggests the need to systematically rank, quantify, and respond to those potential hazards. **Protocols** will be developed to inform operators and regulators on preparing and opening a site, and will serve as the basis for operational standards. Planning for operation geological carbon sequestration will be based on scientific studies (Wilson et al. 2007). It is crucial that these studies occur in the context of large projects (Friedmann 2006; MIT 2007). ***The development of these protocols based on studies at large-scale injection projects should be the highest priority of any decarbonization strategy for most OECD countries.***

Key references and recommended readings

- Benson SM, Cook P, 2005, Chapter 5: Underground Geological Storage, IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Interlachen, Switzerland, www.ipcc.ch , pp. 5-1 to 5-134
- IPCC (2005) Intergovernmental Panel on Climate Change, IPCC Special Report on Carbon Dioxide Capture and Storage , Interlachen, <http://www.ipcc.ch/>
- MIT, 2007, Future of Coal in a Carbon Constrained World, MIT Press <http://coal.mit.edu/>
- NPC, 2007, Facing Hard Truths about Energy: A comprehensive view to 2030 of global oil and gas, National Petroleum Council, Washington, DC, 442 p., www.npc.org
- Pacala S, Socolow R, 2004, Stabilization wedges: Solving the climate problem for the next 50 years using current technologies. *Science* **305**: 986-99
- Thambimuthu K, Soltanieh M, Abanades JC, 2005, Chapter 3: Capture, IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Interlachen, Switzerland, www.ipcc.ch , pp. 3-1 to 3-114
- US DOE, 2007a, Carbon Sequestration Technology Roadmap and Program Plan for 2007, Morgantown, WV, 39p., www.netl.doe.gov.

References cited

- Arts, R., O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer, B. Zinszner, 2004, Monitoring of CO₂ injected at Sleipner using time-lapse seismic data, *Energy*, **29**, pp. 1383-1392
- Bachu S, 2000, Sequestration of CO₂ in geological media: Criteria and approach for site selection in response to climate change. *Energy Conversion and Management* **41**: 953-970
- Bachu S, 2003. Screening and ranking of sedimentary basins for sequestration of CO₂ in geological media in response to climate change. *Environmental Geology*, **44**, 277-289
- Benson SM, Hoversten M, Gasperikova E, Haines M, 2004, Monitoring protocols and life-cycle costs for geological storage of carbon dioxide, 7th International Greenhouse Gas Technology Conference, Vancouver, Canada

- Bradshaw, J, Boreham, C, and la Pedalina, F., 2004, Storage retention time of CO₂ in sedimentary basins; examples from petroleum systems, GHGT-7, Vancouver
- Burton, EA., Myhre R, Myer LR, Birkinshaw K, 2007 Geologic Carbon Sequestration Strategies for California, The Assembly Bill 1925 Report to the California Legislature. California Energy Commission, Systems Office. CEC-500-2007-100-SD, http://www.energy.ca.gov/2007_energypolicy/documents/index.html#100107
- Chiaramonte L, Zoback M, Friedmann S, Stamp V, 2006, CO₂ Sequestration, Fault Stability and Seal Integrity at Teapot Dome, Wyoming, NETL 5th Annual Conference on Carbon Sequestration, Alexandria, VA, ExchangeMonitor Publications
- Edmonds J, Clarke J, Dooley J, Kim SH, Smith SJ, 2004. Stabilization of CO₂ in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, and transportation technologies. *Energy Economics* 26(4):517-537. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.
- Friedmann SJ, 2006, The ICE framework for CO₂ storage site characterization, NETL 5th Annual Conference on Carbon Sequestration, Alexandria, VA, ExchangeMonitor Publications
- Friedmann SJ, 2007a, Operational protocols for geologic carbon storage: Facility life-cycle and the new hazard characterization approach, 6th Annual NETL conference on Carbon Capture and Sequestration, Pittsburgh, PA ExchangeMonitor, Oral 034
- Friedmann SJ, 2007b, Geological Carbon Dioxide Sequestration, *Elements*, v.3, 179-184
- FutureGen Alliance, 2006, Final Request for Proposals for FutureGen Facility Host Site, 54 p. http://www.futuregenalliance.org/news/futuregen_siting_final_rfp_3-07-2006.pdf
- Herzog, H., K. Caldeira and J. Reilly, 2003, An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage, *Climatic Change*, **59**, (3), pp 293-310.
- Hovorka, S.D., Benson, S.M., and 10 others, 2006, Measuring permanence of CO₂ storage in saline formations— The Frio experiment. *Environmental Geosciences* **13**: 103–119.
- IEA GHG, 2005, A review of natural CO₂ emissions and releases and their relevance to CO₂ storage. International Energy Agency Greenhouse Gas R&D Programme, Report 2005/8. <http://www.ieagreen.org.uk/>
- IEA GHG, 2006, 2nd Well Bore Integrity Network Meeting, International Energy Agency Greenhouse Gas R&D, Report 2006/12, September 2006.
- Ide ST, Friedmann SJ, Herzog, HJ, 2006, CO₂ Leakage Through Existing Wells: Current Technology and Regulatory Basis, 8th Greenhouse Gas Technology Conference, Trondheim, Norway, 2006
- Jarrell PM, Fox CE, Stein MH, Webb SL, 2002, Practical aspects of CO₂ flooding. Monograph 22. Society of Petroleum Engineers, Richardson, TX, USA.
- Keith DW, Hassanzadeh H, Pooladi-Darvish M, 2004, Reservoir engineering to accelerate dissolution of stored CO₂ in brines, 7th International Greenhouse Gas Technology Conference, Vancouver, Canada
- Kharaka, YK, Cole, DR, Hovorka, SD, Gunter, WD, Knauss, KG, Freifield, BM, 2006, Gas-water-rock interactions in Frio Formation following CO₂ injection: Implications for the storage of greenhouse gases in sedimentary basins: *Geology*, **34** pp. 577-580.
- Knauss KG, Johnson JW, Steefel CI, 2005a, Evaluation of the impact of CO₂, contaminant, aqueous fluid and reservoir rock interactions on the geologic sequestration of CO₂. *Chemical*

Geology **217**: 339-350.

- Kuuskraa VA, DiPietro P, Koperna GJ, 2006, CO₂ storage capacity in depleted and near-depleted US oil and gas reservoirs, NETL 5th Annual Conference on Carbon Sequestration, Alexandria, VA, ExchangeMonitor Publications
- McFarland, J.R., J.M. Reilly, and H.J. Herzog. 2004. Representing energy technologies in top-down economic models using bottom-up information. *Energy Economics* **26**(4):685-707. Special Issue EMF 19 Alternative technology strategies for climate change policy, John P. Weyant, ed.
- Oldenburg CM, Stevens SH, Benson SM, 2004, Economic feasibility of carbon sequestration with enhanced gas recovery (CSEGR). *Energy* **29**: 1413–1422
- Pacala S, Socolow R, 2004, Stabilization wedges: Solving the climate problem for the next 50 years using current technologies. *Science* **305**: 986-99
- Rao, AB, Rubin ES, Keith DW, Morgan MG, 2006, Evaluation of potential cost reductions from improved amine-based CO₂ capture systems, *Energy Policy*, v34 p. 3765-3772
- Riddiford, F, Wright, I, Espie, T, and Torqui, A, 2004, Monitoring geological storage: In Salah Gas CO₂ Storage Project, GHGT-7, Vancouver
- Stevens S, 1999, Sequestration of CO₂ in Depleted Oil and Gas Fields: Barriers to Overcome in Implementation of CO₂ Capture and Storage (Disused Oil and Gas Fields). IEA Greenhouse Gas R&D Programme, IEA/CON/98/31
- Streit JE, Hillis RR, 2004, Estimating fault stability and sustainable fluid pressures for underground storage of CO₂ in porous rock, *Energy*, **29**, 1445-1456.
- Wilson E, Johnson T, Keith D, 2003, *Regulating the Ultimate Sink: Managing the Risks of Geologic CO₂ Storage*. Environmental Science and Technology, v37, p. 3476-3483
- Wilson EJ, Friedmann SJ, Pollak MF, 2007, Research for deployment: Incorporating risk, regulation, and liability for carbon capture and sequestration, *Environmental Science and Technology* v.41, 5945-5952
- Wilson M, Monea M. (Eds.), IEA GHG Weyburn CO₂ Monitoring & Storage Project Summary Report 2000-2004, 2004, 273 p
- US CCTP, 2005, US Climate Change Technology Program Strategic Plan, Washington, DC., 256 p. <http://www.climatechange.gov>
- US DOE, 2007, Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems. Dept. of Energy Office of Basic Energy Sciences, Washington, 287 p., <http://www.sc.doe.gov/bes/reports/list.html>

This work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.